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Two years of solar wind and pickup ion measurements at comet 67P/Churyumov–Gerasimenko

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ABSTRACT

The Ion and Electron Sensor (IES) as well as other members of the Rosetta Plasma Consortium (RPC) on board the *Rosetta* spacecraft (S/C) measured the characteristics of the solar wind almost continuously since its arrival at 67P/Churyumov–Gerasimenko (CG) in 2014 August. An important process at a comet is the so-called pickup process in which a newly ionized atom or molecule begins gyrating about the interplanetary magnetic field, is accelerated in the process and is carried along with the solar wind. Within a month after comet arrival, while *Rosetta* was <100 km from CG, we began to observe low-energy (<20 eV) positive ions. We believe that these are newly formed from cometary neutrals near *Rosetta* and attracted to the negative S/C potential. These ions were in the early phase of pickup and had not yet reached the energy they would after at least one full gyration about the magnetic field. As CG increased its activity, the flux and energy of the measured pickup ions increased intermittently while the solar wind appeared intermittently as well. By about 2015 end of April, the solar wind had become very faint until it eventually disappeared from the IES field of view. We then began to see ions at the highest energy levels of IES, >10 keV for a few days and then intermittently through the remainder of the mission, but lower energy (a few keV) pickup ions were also observed. As of 2016 early February, the solar wind reappeared more consistently. We believe that the disappearance of the solar wind in the IES field of view is the result of interaction with the pickup ions and the eventual formation of a cavity that excluded the solar wind.

Key words: plasmas – methods: data analysis – comets: individual: 67P/Churyumov–Gerasimenko.

1 INTRODUCTION

Previous missions to comets that included plasma payloads, such as *Giotto* to Halley (Reinhard 1988), *ICE* to comet Giacobini–Zinner (GZ) (von Rosenvinge, Brandt & Farquhar 1986) and *Deep Space 1* (*DS-1*) to comet Borrelly (Nelson, Rayman & Weaver 2004) were fast flybys, allowing only snapshots at instants of time over broad regions of space (but with no repetition of measurements possible) of the plasma properties. The flybys in each of these missions occurred at distances from the nucleus much greater than the distances sampled by *Rosetta* at 67P/Churyumov–Gerasimenko (CG). These missions, however, did provide us with important information about how comets work and allowed comparison of measurements with predictions of models. For example, Johnstone et al. (1987) and Neugebauer et al. (1987) described the results of measurements of plasma structure and characteristics during the *Giotto* flyby of Halley. The structure of the tail of GZ was described by Bame et al. (1986). Richter et al. (2011) have discussed measurements of the magnetic field and plasma during the *DS-1* flyby of Borrelly.

The European Space Agency's *Rosetta* (Glassmeier et al. 2007a) spacecraft (S/C) was launched from Kourou, French Guiana, on 2004 March 2, arrived at comet 67P/Churyumov–Gerasimenko (CG) in 2014 August, and was orbiting mostly within a few

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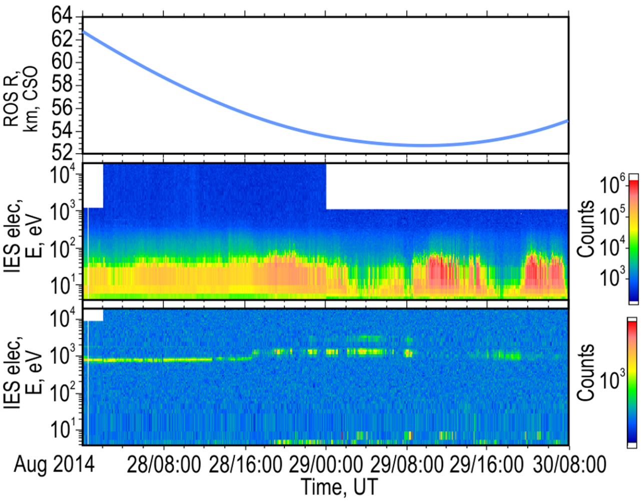

Figure 1. Energy–time spectrograms of the SW: electron (middle panel) and ion (lower panel) IES measurements during 2014 August 28 and 29. Note the shock at 16:00 UT. Distance to CG is shown in the top panel. The white areas are the result of changes in operating mode.

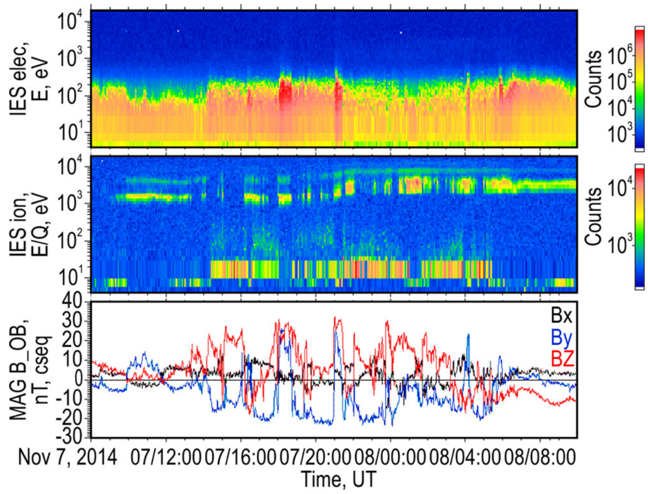

Figure 2. Energy–time spectrogram of electrons (upper panel) and ions (middle panel) measured during 2014 November 7 and 8. SW protons and alphas are at 1 and 2 keV, respectively, while the few hundred eV signal is from pickup ions. Components of the magnetic field measured by the outboard magnetometer are shown in the lower panel.

hundred km of CG since arrival and until the end of mission on 2016 September 30. The Rosetta Plasma Consortium (RPC; Carr et al. 2007) consists of five plasma instruments on board *Rosetta*: the Ion Composition Analyzer (ICA; Nilsson et al. 2007), the Ion and Electron Sensor (IES; Burch et al. 2007), the Langmuir Probe (Eriksson et al. 2007), the Mutual Impedance Probe (Trotignon et al. 2007), the magnetometer (Glassmeier et al. 2007b) and the Plasma Interface Unit (Carr et al. 2007). We have previously reported on the results of plasma measurements by RPC instruments: Goldstein et al. (2015), Broiles et al. (2015, 2016), Clark et al. (2015), Burch et al. (2015a,b)and Nilsson et al. (2015a,b) as the comet began its activity. This report is a summary of some of the results of RPC-IES measurements of the solar wind (SW) (or its absence) as well as the characteristics of pickup ions over the course of the mission's two years in the vicinity of CG (see Appendix).

2 INSTRUMENTATION AND EARLY OBSERVATIONS

The RPC-IES instrument measured ion and electron flux as a function of energy (4.3 eV to 17.7 keV) and direction (360° azimuth on 16 anodes and ±45° elevation stepped over 16 bins). See Burch et al. (2007) for details. Fig. 1 is an example of an energy–time spectrogram of SW electrons (middle panel) and ions (protons and intermittently, alpha particles, lower panel) measured by IES during 2014 August 28 and 29, within a month of *Rosetta's* arrival at CG. (The white areas in the electron portion is the result of changes in IES operating mode using different energy ranges.) The upper panel shows the distance of *Rosetta* to CG during this period.

During this period, *Rosetta* was 3.47 au from the Sun, moving towards perihelion at 1.24 au in 2015 August. Note what appears to be an SW shock around 16:00 UT on the 28th. We estimate the velocity jump to have been approximately from 360 to 400 km s^{-1}, accompanied by a factor of 2 increase in density in front of the discontinuity. In addition to the jump in proton energy, the electron flux has also increased. Furthermore, there is a sudden appearance of low-energy ($<$20 eV) ions shortly after the increase in electron flux. We believe that these are newly formed from cometary neutral molecules or atoms near *Rosetta* and attracted to the negative S/C potential due to the increase in electron density (Broiles et al. 2015; Goldstein et al. 2015). *Rosetta* was 50 km to CG, so ions created locally were in the early phase of pickup and had not yet reached the energy they would attain after at least one full gyration about the magnetic field, hence could be drawn to the S/C by its weak electric field. Ions created far enough away (see Section 3) would have been accelerated to much higher energies. [See fig. 6 of Rubin et al. (2014) for a discussion of the beginning of the pickup process and fig. 1 of Goldstein et al. (2015), which also shows the relation of these ions to the local neutral density.] We observed such low-energy ions almost continuously since then until the end of the mission.

By 2014 early November, IES began to detect pickup ions of energies up to several hundred eV. Fig. 2 shows plots of data measured on 2014 November 7 and 8. The upper panel is an energy–time spectrogram of electrons measured by IES, the second panel is a similar spectrogram for ions and the bottom panel plots the magnetic field components measured by the magnetometer (Glassmeier et al. 2007b). *Rosetta* was 3 au from the Sun and 30 km from CG at that time. SW ions are seen intermittently, protons at 1 kev and He^{++} at 2 keV, although these energies begin to increase at 18:00 UT. The 20 eV ions described in the previous figure appear here as well, along with, very diffusely, ions of energy up to about several hundred eV. The magnetic field shows considerable variation during the period from about 13:00 UT on February 7 to 07:00 UT on the 8th, coinciding approximately with the increases in the electron and pickup ion flux. Most striking are the (in-phase) pulse structures of the *y*- and *z*-field components at 18:00 and 22:00 UT on November 7, while the *x*-component remains relatively constant. This means that there are two linearly polarized (45° in the *yz* plane) structures occurring at those times. These structures could be caused by a tilted current sheet passing the S/C.

An energy polar plot of the ion data of this figure from 16:00 to 18:00 UT on November 7 is shown in Fig. 3. The 22°.5 divisions in azimuth of the detector are numbered in order to identify and orient the look directions. The log of the energy is given by the radius and the colour bar shows the measured energy flux. The anti-Sun

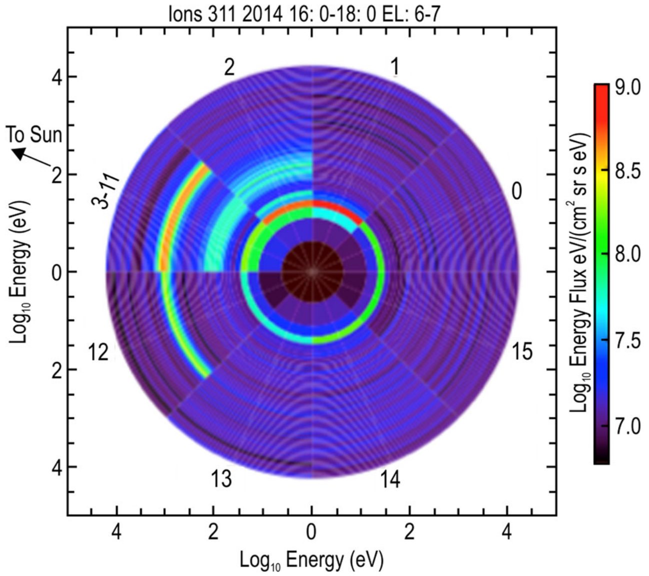

Figure 3. Polar plot of ion data between 16:00 to 18:00 UT on 2014 November 7. The 16 anodes in the IES azimuth plane are numbered. The antisolar direction is towards anodes 3–11, and the comet nucleus points between anodes 13 and14.

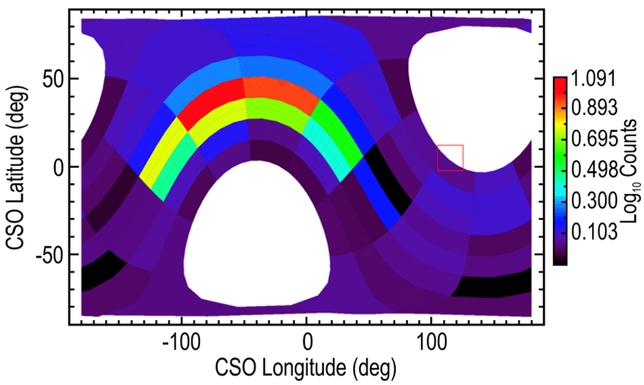

Figure 4. Plot in the CSO coordinate system of a portion of the ion data used for Fig. 3. The Sun is at (0,0), and the location of the comet in the IES FOV is given by the red square. Each coloured element is an IES azimuth–elevation pixel.

direction is to the anode 3–11 group, although the SW also appears to be spread towards anode 12, 22°.5 away from that direction. Perhaps that accounts for its 'smeary' appearance in Fig. 2. The several hundred eV ions appear to come mostly on anode 2, within 22°.5 from the antisolar direction, which would be expected for ions picked up and carried along with the SW. Fig. 3 is in an IES-centric coordinate system. Instead, in order to more directly relate to the comet and Sun, we will use the comet solar orbital (CSO) system for plotting IES data. In this system, the origin is at the comet, 0° longitude is towards the Sun and latitude is measured northwards from the comet orbital plane. Fig. 4 is an example of the data plotted in Fig. 3 as it appears in the CSO system. This plot explicitly shows both the elevation as well as azimuth, i.e. the IES field of view (FOV) for the time and energy given. The coloured elements are azimuth–elevation pixels. The Sun is at coordinates (0,0) and the location of the comet in the IES FOV is given by the red square. The odd-shaped holes in the FOV are a result of the elevation angle limit of ±45° and the location and attitude of *Rosetta* at the time of the data. Two

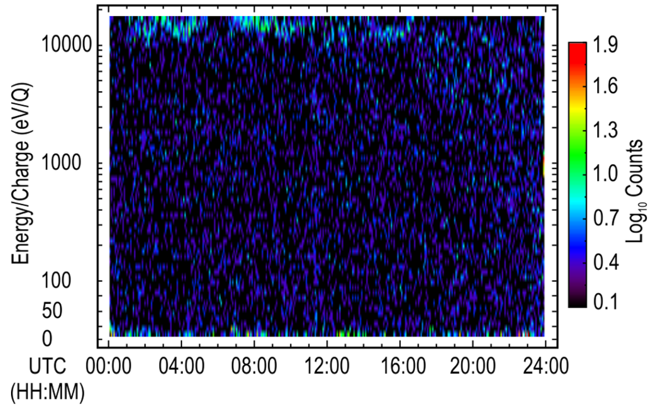

Figure 5. Ion energy–time spectrogram for 2015 April 19 from IES measurements, showing the appearance of high-energy ions. The very low energy ions were created locally and attracted by the negative S/C potential. The high-energy ion counts correspond to the IES anode 2 (solar direction) and elevation channels 0–1 (45° in the IES frame). *Rosetta* was 105 km from CG, which was 1.8 au from the Sun at this time. The colour bar shows the measured ion count level.

MP4 videos are included in the Supplementary Information section available online, one of which shows a time-stepped series and the other shows an energy-stepped series of the data for Fig. 4. These correspond to a portion of the data in the spectrogram of Fig. 2 and a portion of the data used for Fig. 3. The videos show that for a given energy range, the location of the count rate peak in the IES FOV moves around during the period of the video, although the S/C pointing was relatively steady during this period.

3 OBSERVATION OF HIGH-ENERGY PICKUP IONS

During 2015 mid-April, the *Rosetta* S/C was travelling in an approximately triangular (about 100 km per side) trajectory about CG, 20 km sunwards of it. *Rosetta's* speed was about 0.5 m s^{-1} relative to CG. The ion data for 2015 April 17, for several days following and intermittently during the following month, began to show the presence of ions of energy at the highest level of the IES capability ($\gtrsim$17 keV), which we had previously never seen in IES or ICA data. The evolution of the ICA data was shown in Nilsson et al. (2015a), with water ion energies typically not reaching much above a few keV. The IES electron data show an increase in flux by a factor of about 2 in the energy range up to 100 eV during this time period, but it is not clear whether that is related to the appearance of the high-energy ions. *Rosetta* was 100 km from CG, which was 1.8 au from the sun at that time. Fig. 5 is an IES ion energy–time spectrogram for 2015 April 19, showing the appearance of these newly observed very high energy ions appearing in anode 2 (Sun pointing) at an elevation angle of 45°. We believe these ions to be the result of neutral water molecules that have moved far from the nucleus as the coma expands, becoming ionized by solar ultraviolet or other processes, picked up by the SW and accelerated by the pickup process as they are carried back towards the comet. Such an antisunward flow is typical for the water ions observed with ICA (Nilsson et al. 2015b), though normally at much lower energy. Also seen in Fig. 5 are the very low energy ions locally formed and attracted to the S/C by its negative potential (Goldstein et al. 2015).

The maximum velocity of an ion picked up by the SW is twice the SW speed. Hence, the maximum energy for pickup protons would be four times the SW proton energy, or, typically, 4 keV. We believe

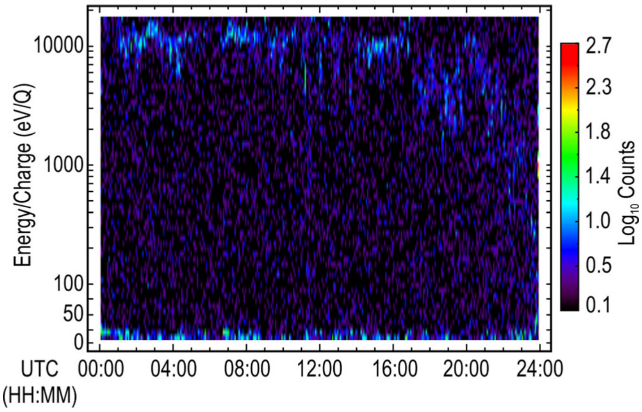

Figure 6. Ion energy–time spectrogram for the same conditions as those for Fig. 5 except that the elevation channels were 4–5 (30° in the IES frame).

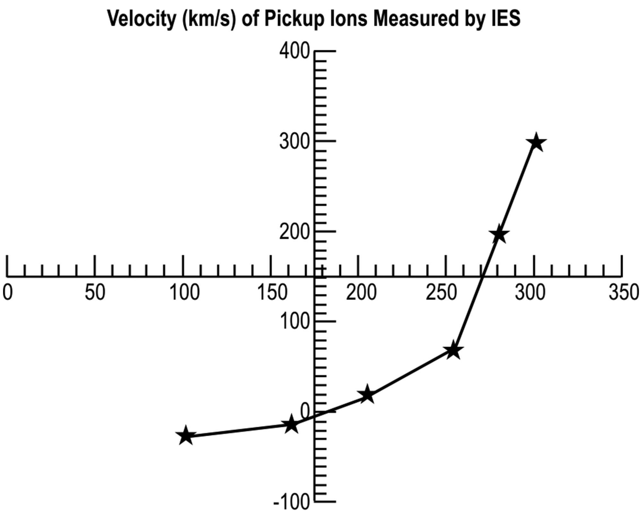

Figure 7. Ion energy measured by IES at different IES elevation angles for 2015 April 19, suggesting the formation of a pickup ion shell. See also Figs 5 and 6.

therefore that the $\gtrsim$17 keV ions must be more massive than protons, and we assume that they are water molecule ions (based on the ICA measurements), which would have a maximum pickup energy of $4 \times 18 = 72$ keV. The mean density and velocity of these high-energy ions, assumed to be water, from a moment calculation on the measured count rates are 33 cm^{-3} and 420 km s^{-1}, respectively.

Fig. 6 shows the IES ion data at an elevation angle of 30°, and an energy of 6 keV from 0:00 to about 16:00 UT on this day, and decreasing in energy after that. Comparison of Figs 5 and 6 suggests an energy distribution as a function of angle, and in fact, the apparent ion energy did decrease further with additional elevation angle steps. Fig. 7 is a plot of the measured ion velocity between 0:00 and 8:00 UT as a function of the IES elevation angle for 2015 April 19 (with arbitrary axes). The dependence on energy suggests that these ions form a ring or shell, typical geometries for a developed pickup ion distribution (e.g. fig. 1 in Neugebauer et al. 1987).

4 DISAPPEARANCE AND REAPPEARANCE OF THE SOLAR WIND

Around the time that these high-energy pickup ions appeared, the SW gradually disappeared from the IES FOV. Fig. 8 shows this

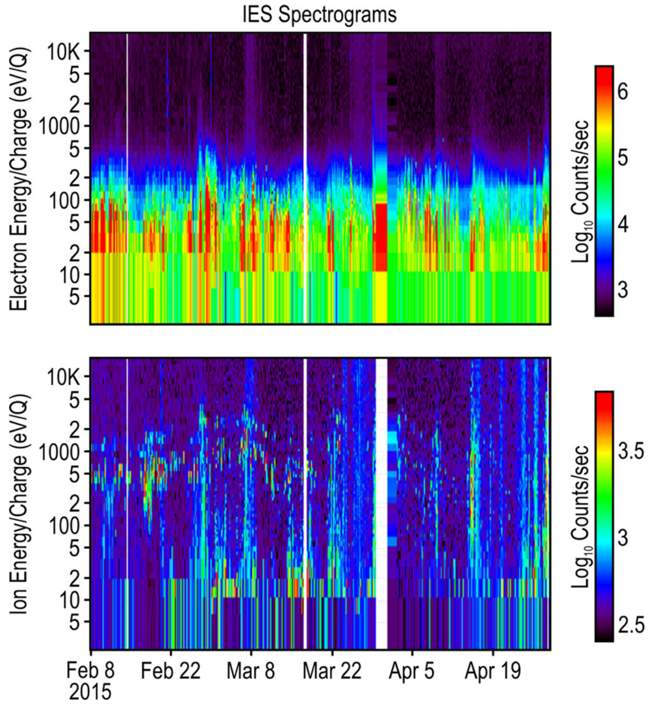

Figure 8. Ion and electron count rates measured by IES showing the gradual disappearance of the SW ions in the IES FOV during approximately 2015 early March to the middle of April.

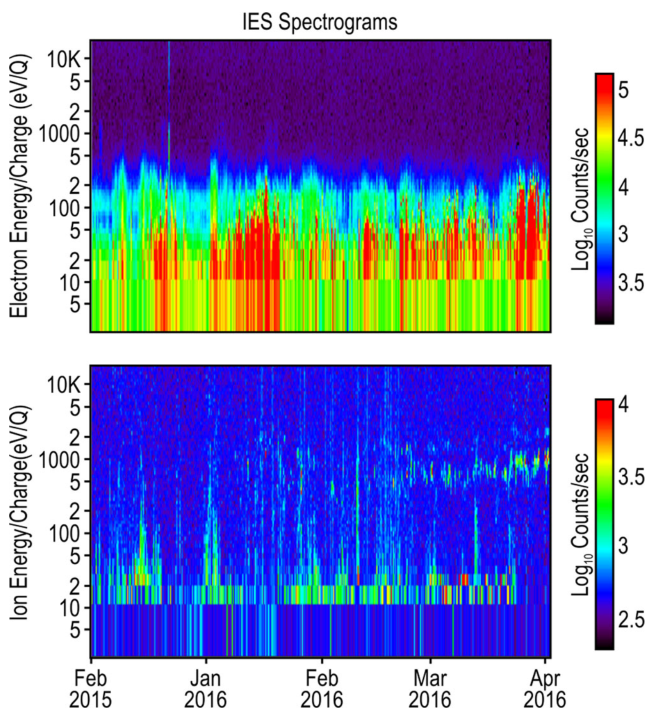

Figure 9. Ion and electron count rates measured by IES showing the gradual return of the SW in the IES FOV during approximately 2016 mid-January to the middle of March.

decline over the period from 2015 early March to the end of April. The SW eventually reappeared in the IES FOV in early 2016, as shown in Fig. 9. We believe that this disappearance and reappearance are the result of the interaction of the SW with the pickup ions, causing a deflection of the SW out of the IES FOV. Such a

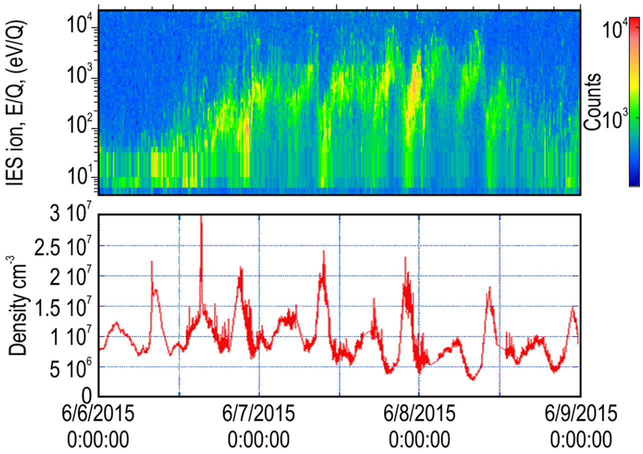

Figure 10. Energy–time spectrogram for the duration 2015 June 6–9. Upper panel: pickup ions flowing antisunward measured by IES. Lower panel: neutral density measured by the ROSINA-COPS instrument.

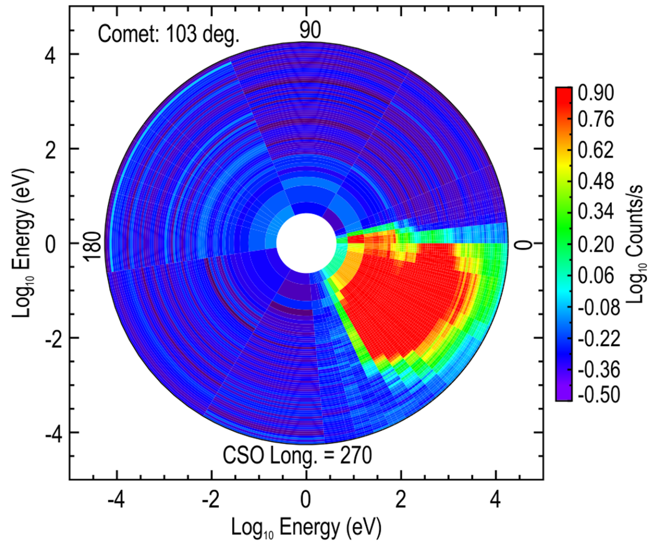

Figure 11. Ion energy–angle contour plot in the CSO system, from IES measurements during 9:00 to 17:00 UT on 2015 June 7, in the energy/charge range 10–17 600 eV/Q. In this coordinate system, the Sun is at 0° longitude and CG at 103°. Most of the ions are coming from within 20° of the solar direction.

deflection was first discussed by Chapman & Dunlop (1986) in connection with the AMPTE plasma releases, and was described previously for CG (Broiles et al. 2015; Goldstein et al. 2015). The deflection over the period from 2014 September to the end of the mission in 2016 September was measured by the ICA component of RPC and discussed in Behar et al. (2016, 2017) as the result of the exclusion of the SW, forming a cavity.

Also during this period, *Rosetta* moved sunwards to about 1500 km (on 2015 September 30) to explore the plasma in this region and in the hopes of encountering a bow shock. No indication of a shock was observed, but a number of other boundaries of interest were seen (Mandt et al. 2016). A second (tail) excursion from CG was performed in the antisunward direction, reaching 1000 km from the comet on 2016 March 30.

During the period of absence of the SW in the IES FOV, the instrument continued to see pickup ions intermittently over a range of energies, such as described in Figs 5–7.

An example of the coma plasma measured during 2015 June 6–9 is shown in Fig. 10. *Rosetta* was about 200 km from CG and both were about 1.5 au from the Sun during this period. The top panel in the figure is an energy–time spectrogram of ions measured by IES. The lower panel shows the local neutral gas density, assumed to be primarily water molecules, measured by the on board COPS (Comet Pressure Sensor) portion of the ROSINA (Rosetta Orbiter Spectrometer for Ion and Neutral Analysis) sensor (Balsiger et al. 2007). There appear to be at least two sets of periodic peaks of the neutral gas, each with a period of 12 h, but shifted 6 h from each other. The periodicity is presumably related to the 12 h nucleus rotation period. The stronger gas peaks are mostly closely coincident with the deeper dips in the ion peaks, while the weaker gas peaks tend to be closely coincident with the weaker ion dips. These ions were flowing within 20° in the antisunward direction, and we conclude that they are pickup ions travelling with the SW, although the SW itself was not within the IES FOV at that time. Fig. 11 is a contour plot in CSO coordinates of the ion count rate for the period 9:00 to 17:00 UT on 2015 June 7, which shows the direction from which the ions are flowing. The Sun is at 0° in this coordinate system so the ions are coming from within 20° of antisunward, consistent with our suggestion that these ions have been energized by their pickup by the SW. Similar to the measurements for 2015 April, the 2015 June data also show the presence of ions at $\gtrsim$17 keV energy. There may be other mechanisms responsible for the high energy (such as excitation by waves), but we believe that the most plausible is by the pickup process since that tends to be ubiquitous at comets. Aside from the presence of very high energy ions, of note is the apparent periodicity of the ion peaks, with a period of 12 h, close to the nucleus rotation period, suggesting a connection with gas production from a specific location on the nucleus. This relationship had previously been observed with the IES-measured electron density in 2014 (Goldstein et al. 2015), although at $\gtrsim$6 h, half the period seen here. That was thought to be the result of seeing the same source twice in one rotation of the nucleus. In that observation, increases in the electron flux coincided with the neutral gas peaks. We estimate that the average density of the ions shown in Fig. 10 is 33 cm^{-3}, about several orders of magnitude lower than the ambient neutral density shown in the same figure. We suggest that the neutral gas interacts with the flow of the much less dense ions, possibly by charge exchange, producing the pattern seen in Fig. 10. We estimate the ion average speed to be 15 km s^{-1}, in contrast to the neutral speed 0.7 km s^{-1} measured by the MIRO instrument (Gulkis et al. 2007) on board *Rosetta*.

When the SW began reappearing in the IES FOV in early 2016, it was at an unusually low energy: 400 eV for the protons, and very variable. There were also not many pickup ion observations during 2016 presumably as a result of the decreasing activity of the comet. Although the S/C orientation during *Rosetta's* final descent was not ideal for IES, we were able to catch a final glimpse of the SW during the last three days, as shown in the ion energy–time spectrogram of Fig. 12. Note that in order to obtain this farewell image, it was necessary to choose very limited look directions in the data, specifically pointing only to the Sun.

5 SUMMARY AND CONCLUSION

The RPC-IES instrument studied the SW, cometary plasma and pickup ions in the vicinity of CG during the approximately 2 yr that the *Rosetta* S/C was in the vicinity of the comet. The SW interacted strongly with the pickup ions, turning away significantly from its normal antisunward direction for much of 2015 and part

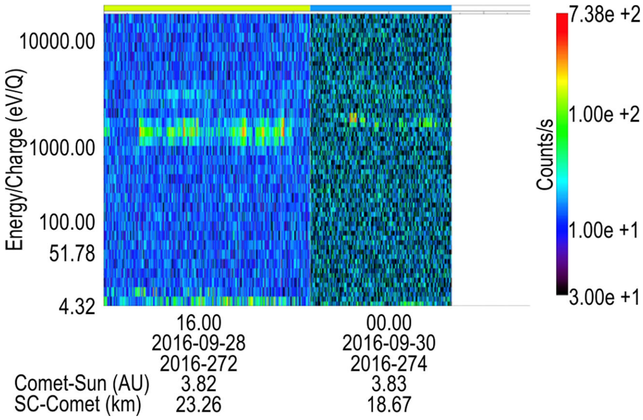

Figure 12. IES ion energy–time spectrogram during the last three days of the *Rosetta* mission, 2016 September 28–30. The S/C impacted the nucleus just after the last data were received. Note that the IES operation mode changed at about 08:00 UT on September 29.

of 2016. High-energy ($\gtrsim$17 keV) pickup ions (presumably water) have been measured intermittently beginning in 2015. The neutral coma gas appears to interact with the flow of the antisunward-moving pickup ions at times, possibly as a result of charge-exchange reactions between the two. Since the neutral gas density is often quasi-periodic as a result of the nucleus rotation, this sometimes introduces a quasi-periodic character to the pickup ion flux.

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SUPPORTING INFORMATION

Supplementary data are available at *MNRAS* online.

MP4 videos: showing a time-stepped series and an energy-stepped series of the data for Fig. 4.

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APPENDIX

The IES data used for the preparation of this report are available from both the NASA PDS (https://pds.nasa.gov/) and the ESA PSA (https://archives.esac.esa.int/psa/) archive web sites. Level 3 IES data (differential energy flux) have also been submitted and are currently under review. Questions about the use of these resources may be sent to the author.

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